

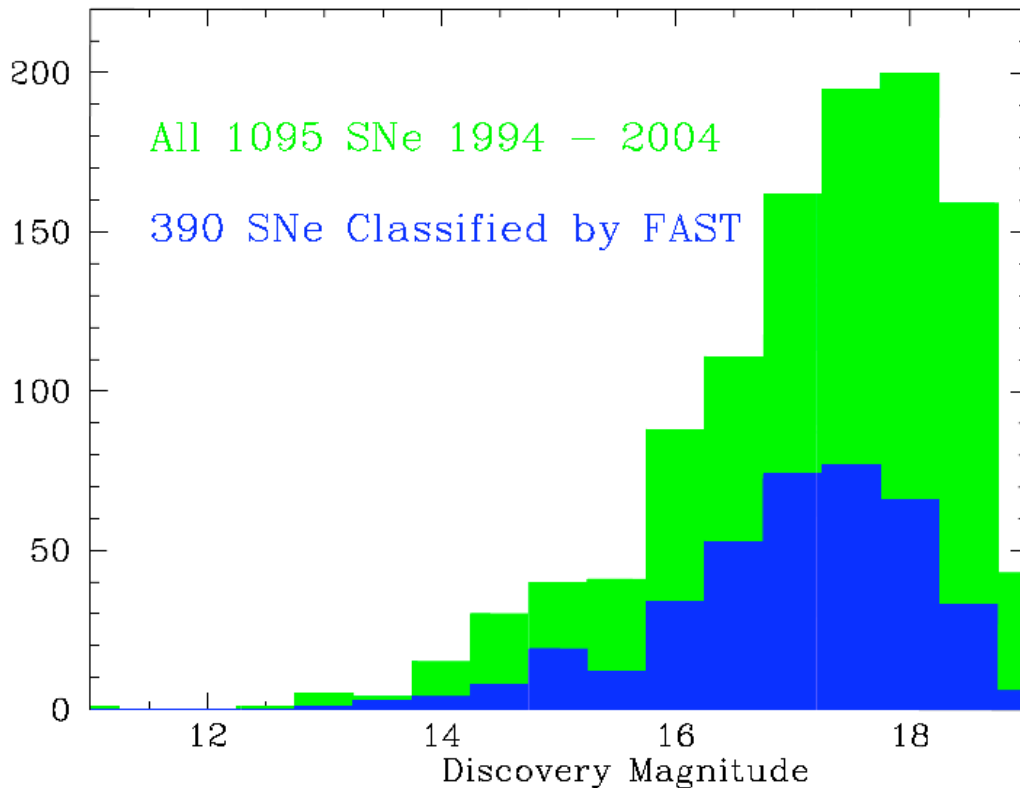
**Supernova Observations:
Foundation of the Accelerating Universe**
A White Paper for the Dark Energy Task Force
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Project Description: The Supernova Program at the Center for Astrophysics obtains low-dispersion optical spectra, UBVRI and JHK infrared light curves for almost every supernova brighter than 18th mag and north of -20 . Diligent searching among the IAU Circulars and rapid remote access to our 3 telescopes at Mount Hopkins, AZ has led to the world's largest database of SN Ia observations. We doubled the world sample of well-observed SN Ia light curves, we have doubled it again (to ~ 95), and, just by staying on the same trajectory, we will again double the sample to well over 200 zero-redshift light curves by 2007. This is the low redshift foundation for measuring cosmic acceleration from the Hubble diagram.

By 2007 the statistical errors resulting from the low redshift supernovae will be insignificant in analyses of the cosmological parameters. The photometric precision is typically 3% or better. We have already used our sample to develop the **M**ulticolor **L**ight **C**urve **S**hape (MLCS) method. MLCS has been used effectively by the High-Z Team to establish one of the strong strands of evidence that we live in an accelerating Universe that needs dark energy (and a Dark Energy Task Force.) The first measurement of w was carried out using our low- z data together with the results from the High-Z Supernova Team (Garnavich 1998). Our unique U-band collection was at the heart of the amazingly successful work by the Higher-Z Team using HST to establish the evidence for cosmic jerk: the deceleration due to dark matter that preceded the current era of acceleration. This work provided the first limits on w' (Riess et al 2004). We will use this burgeoning sample to pin down the low redshift end for the ESSENCE (**E**quation of **S**tate: **S**upernovae trace **C**osmic **E**xpansion) program at $z \sim 0.5$ and for the HST-based **P**robing **A**cceleration **N**ow with **S**upernovae (PANS—Adam Riess, P.I.) work being carried through this year at $z \sim 1.4$. It will be of direct application to any future Dark Energy Probe, eliminating the zero redshift sample as a source of statistical uncertainty.

The spectroscopic database obtained at the CfA is also the largest in the world, with over 1500 supernova spectra, all obtained with the same spectrograph. We are using this extensive database to examine the spectroscopic variations among SN Ia. Understanding the causes of the variations in SN Ia in the zero redshift sample may prove to be the key to reducing systematic uncertainties in the cosmological sample.

The Observing Program: This histogram shows that 35% of the supernovae reported in the IAU Circulars in the past decade had their supernova type determined by CfA observations with the FAST spectrograph at Mount Hopkins.



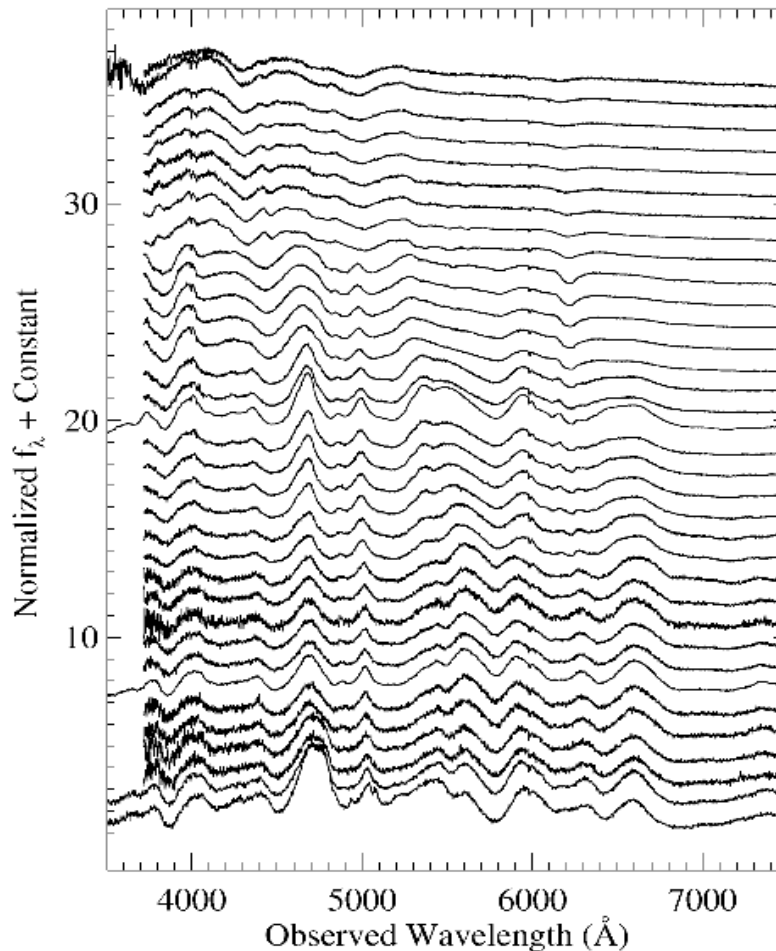
Photometric observations are obtained at the F.L. Whipple Observatory (FLWO) at Mount Hopkins, Arizona, using proxy, remote, and scheduled observing at the 1.2 meter telescope for UBVRI photometry. The forthcoming summary of these observations prepared by Saurabh Jha (2005) reports 2190 photometric observations of 44 SN Ia obtained on 338 nights. This is the largest homogeneous collection of SN Ia data which, when added to the 22 objects from this program previously published by Riess et al (1999) makes the CfA the world's largest source of fundamental data on these essential distance-measuring tools for cosmology. Today's state-of-the art data set for SN Ia has 95 low- z objects in the Hubble Flow. About 25% of these are from the Calan/Tololo Survey (Hamuy et al. 1996) and most of the rest are from the CfA.

Jha's paper, an extension of his Ph.D. thesis, is also the first large set of published U-band observations. He shows that the U-band provides a good measure of the time of maximum light and light curve decline rate. This means that U-band observations can augment restframe B-band and V-band observations for medium and high redshift supernovae. Even at $z \sim 0.25$, the

observer's B-band is observing restframe U. Riess et al. (2004) used this U-band approach to establish distances to SN Ia at $z > 1$. Those HST data establish the fact of an era of cosmic deceleration that preceded the present epoch of cosmic acceleration, with a transition near $z=0.46 \pm 0.13$. The low-redshift U-band sample from the CfA was an essential aspect of this HST-based approach to establishing a mixed dark matter/dark energy universe that places the most stringent constraints to date on the properties of dark energy. Augmenting this limited U-band sample will improve the cosmological inferences up to the point where they are limited by the precision of the flux calibration.

Spectroscopic observations are obtained at the 1.5 meter telescope at FLWO with the efficient FAST CCD spectrograph (Fabricant et al. 1998) by a resident observer as needed each night. Results from this rapid response to discoveries are promptly communicated to interested parties, posted to <http://cfa-www.harvard.edu/cfa/oir/Research/supernova/RecentSN.html> and reported to the IAU Circulars.

SN 2001V—SPECTRAL SERIES

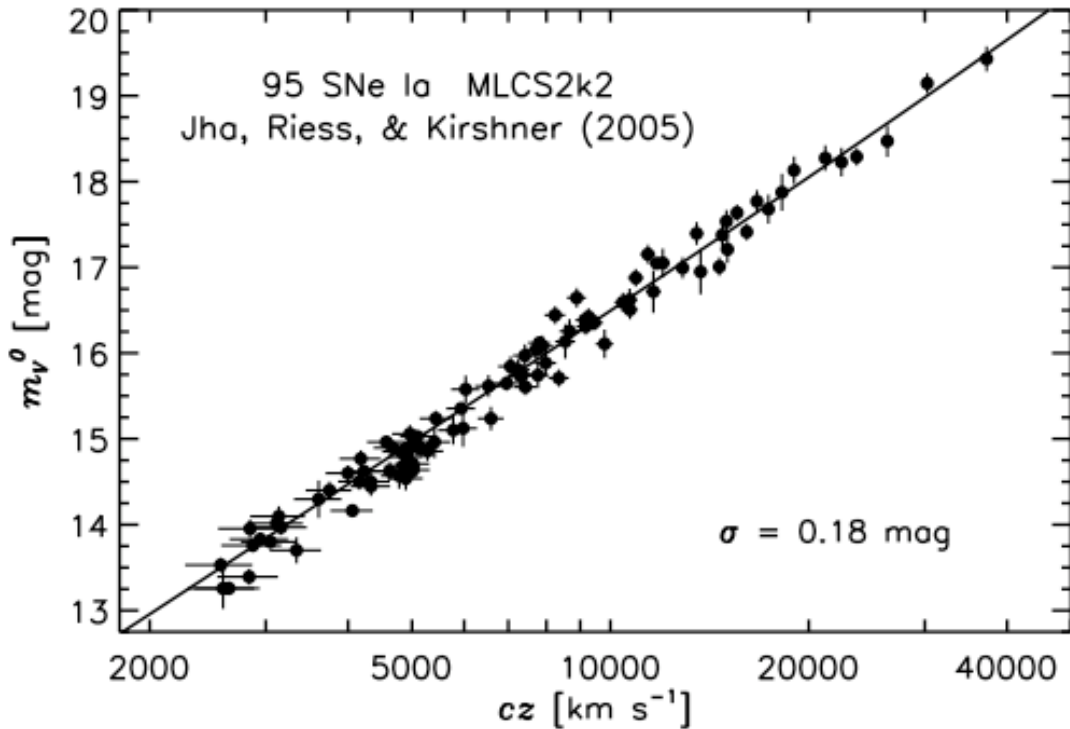


Our spectroscopic work goes far beyond classification. We often obtain excellent series of nightly data that can be used for more thorough investigation of the physics of SN Ia. We now have a collection of 1548 spectra for 243 SN Ia: 16 supernovae have more than 20 epochs of spectroscopy. The work underway includes studies of line strengths and velocities and their correlation with supernova luminosity. Preliminary results are similar to those obtained by Benetti et al. (2004), but employ a much larger and more homogeneous sample. For example, the relative strength of the hallmark Si II lines shows a strong correlation with the supernova luminosity. All our spectra will be made publicly available after the first comprehensive analysis by Tom Matheson is published this year.

Following the keen insight of Phillips (1993), we have explored ways to use the shape of the supernova light curve to decrease the scatter in the Hubble Diagram, both at low redshift where this helps with establishing the Hubble Constant (Jha et al., 1999) and large scale galaxy flows (Radburn-Smith et al. 2004), and at redshifts greater than 0.3, where the combination of high- z SN Ia data and the low- z sample described here provides evidence for the effects of dark energy.

Our approach was sketched in Adam Riess' Ph.D. thesis. This Multicolor Light Curve Shape method (MLCS) takes into account the shape of the light curve as observed in several photometric bands to derive the luminosity distance to the supernova in question. In his thesis, Saurabh Jha took this work another step forward, developing a more satisfactory treatment of reddening, extending the method to incorporate U-band information, and allowing for non-linear terms in the relation between light curve shape and luminosity. All of this mathematical machinery, which we call MLCS2k2, is in service of making accurate and precise distance measurements. Based on scatter in the Hubble Diagram, for objects in the Hubble flow beyond 2500 km/sec, the distance uncertainty to a single well-observed supernova is below 9%, making the SN Ia the best extragalactic standard candles.

Since there are now some dozens of galaxies whose distances are well known from HST observations of their Cepheids, it is a reasonable proposition to turn the problem around and ask not just for small scatter in the Hubble Diagram, but for calibration of the luminosity and a determination of the Hubble Constant. The intercept in the SN Ia Hubble Diagram below is determined to 0.025 mag, well below our expectation for the accuracy of the absolute calibration. In other words, the supernova part of this problem is now done—essentially all the uncertainty in the Hubble Constant resides in the Cepheids and the underlying measurement of the distance to the LMC.

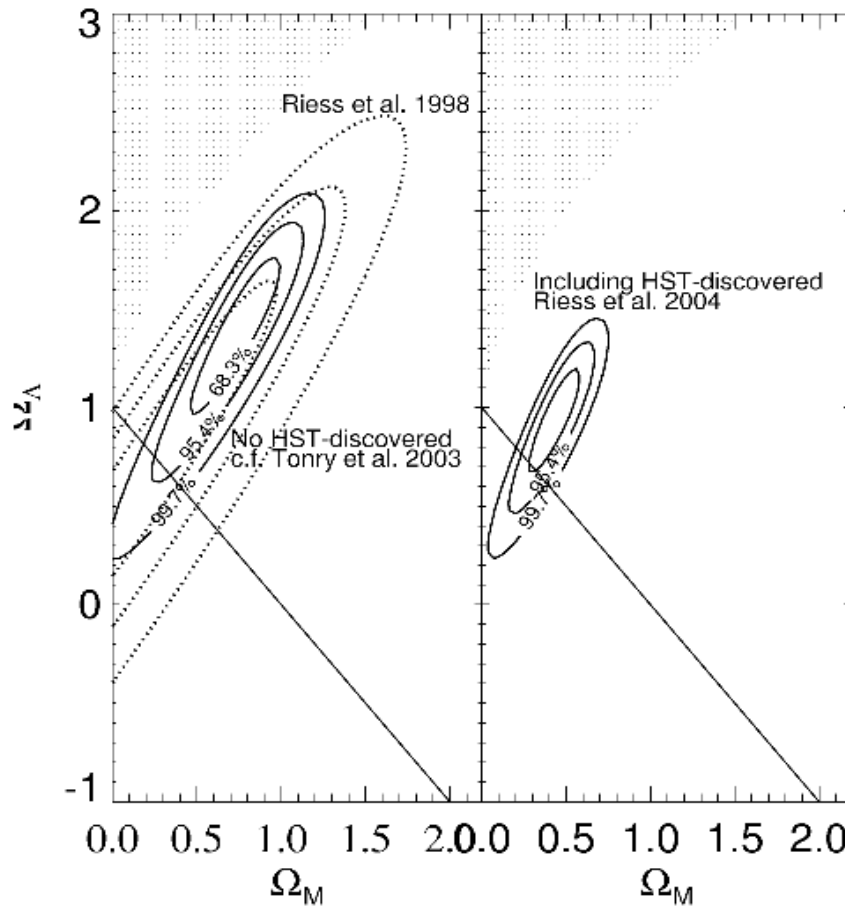


Jha analyzed our extensive data on SN 1998bu in M96, a galaxy for which HST Cepheid observations had previously been carried out. Based on the sample at that time of 40 SN Ia (18 observed at the CfA), using Key Project distances, Jha inferred a Hubble Constant of $H_0 = 72 \pm 7$ km/sec/Mpc. As the sample of well-observed supernovae grows, the early expedient of using every possible SN Ia adopted by Sandage and his collaborators (Saha et al. 2001) and by the Key Project (Gibson et al. 2002) is no longer necessary. We can find H_0 without using the prehistoric observations of SN 1937C and SN 1960F, the highly reddened supernova SN 1989B, or the unusual supernovae SN 1991T and SN 1999by. The way forward is to use our superb observations of absolutely typical supernovae in low-reddening settings to do the calibration. This is now possible, as shown by Riess et al (2005), where CfA observations of SN 1994ae and SN 1998aq are combined with Cepheid observations from the Advanced Camera for Surveys on HST to calibrate the rich nearby Hubble diagram and to determine $H_0 = 73 \pm 6$ km/sec/Mpc. There will be more supernovae found in galaxies for which distances are already known to improve this "prior" constraint on the cosmology. By 2008, the uncertainty in the Hubble Constant measured this way could be smaller than 5%.

Measuring H_0 is still important. The legend of WMAP having established all the cosmological parameters to good precision is powerful, but a bit misleading. As Spergel et al. (2003) point out, a well-established independent value for H_0 tests the model used to fit CMB fluctuations. What is more, the Ω_Ω , Ω_m values that fit both low and High-Z supernova

observations on the Hubble Diagram of (0.71,0.29) provide a very good constraint on the dimensionless quantity $H_0 t_0$. From the recent work of the High-Z Team (Tonry et al. 2003), we find $H_0 t_0 = 0.96 \pm 0.04$. With knowledge of H_0 through SN Ia, this gives solid information on t_0 , the elapsed time since the Big Bang, of 13.6 Gyr. By comparing this time with completely independent chronometers, such as the white dwarf cooling sequence or the radioactive half-life of elements in very old stars, we have the possibility to develop a wider web of evidence to establish the cosmological parameters.

Measuring cosmic acceleration from supernovae has been astonishing, as recognized by Science Magazine when they dubbed it the "Science Breakthrough of the Year" in 1998. Since then the case has gotten stronger due to the convergence of evidence from the CMB and galaxy clustering, but the data from the supernovae themselves have also been substantially improved. Both the low and high redshift samples have been doubled in number (Tonry et al. 2003, Barris et al 2003) improved in precision (Jha 2005, Knop 2003), and extended in redshift reach (Riess, 2004).



The Ω_0, Ω_m figure shows the current state of play, using the CfA and Calan-Tololo samples at low redshift (included in the "Gold" sample of Riess et al

(2004)) analyzed according to the precepts of MLCS2k2. The error ellipse has decreased by a factor of 5 in 5 years. By 2008, the combination of the 200 CfA SNIa, and similar numbers from Carnegie and the Supernova Factory data at low redshift, the 200 ESSENCE and larger CFHT Legacy data at moderate redshift and the PANS work of a few dozen at high redshift promises another step forward whose precision will be limited only by the care of calibration, not by the size of the low- z sample. The error ellipse will surely shrink by another factor of two or more based on the sample size, but further progress will depend on scrupulous attention to matters of photometric calibration.

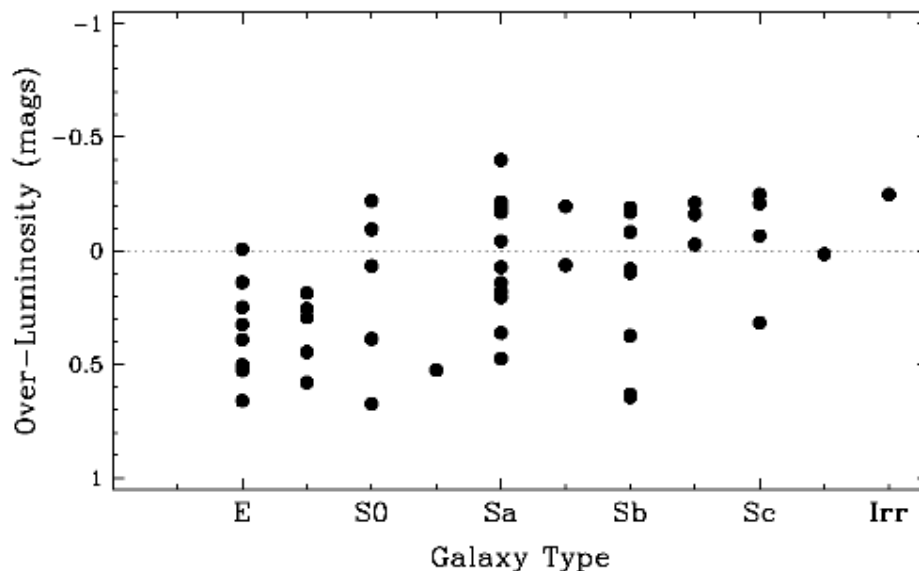
Constraints on dark energy: We were the first to analyze the Hubble Diagram for SN Ia to derive the equation of state for Dark Energy (Garnavich et al. 1998). We showed that the observed onset of acceleration is completely consistent with the expected equation of state for a (ridiculously small) cosmological constant, expressed as $w = -1$, where $p = w\rho$, and the relation between the cosmic scale factor and ρ is then $\rho = a^{-3(1+w)}$. It is exceedingly important for fundamental physics to measure the amount of dark energy, and then to find out whether the Dark Energy is the cosmological constant, or something else. The present constraints, from Riess et al (2004) place a 3 σ upper limit $w < -0.72$, and have a best value (for a flat universe) of $w = -1.02$ which already rules out some possibilities for the source of the dark energy and is completely consistent with a cosmological constant. In the near future, the work being done through the ESSENCE program, parallel work being done through the CFHT Legacy program, and continued work at higher- z by the PANS group on HST led by Adam Riess will provide stronger constraints, at the 10% level, for w and improved constraints on w' . The low- z sample from the CfA will be large enough to contribute only a few percent to the uncertainty. This cannot fail to be interesting: either the results will be consistent with the cosmological constant, whose value we do not understand, or they will point to another form of the dark energy, which we also do not understand.

One More Doubling of the Sample: The precision of cosmological parameters from SN Ia will, in the future, depend principally on systematic errors, not statistical errors from the finite sample size. Although that future is just around the corner, it isn't here yet. The data we have in hand includes 5820 photometric observations in UBVRI. From this big data set, we expect to get first-rate light curves for 46 additional SN Ia for which we have photometric observations at 10 or more epochs.

There are ambitious efforts by others to do similar work, notably the Katzman Automatic Imaging Telescope, the Carnegie Supernova Program and the Nearby Supernova Factory. The results of these energetic observing programs will eventually become comparable to the CfA effort. But the present number of published light curves from CSP and NSF is much smaller. It is exactly one so far, SN 2002ic (Wood-Vesey et al 2004).

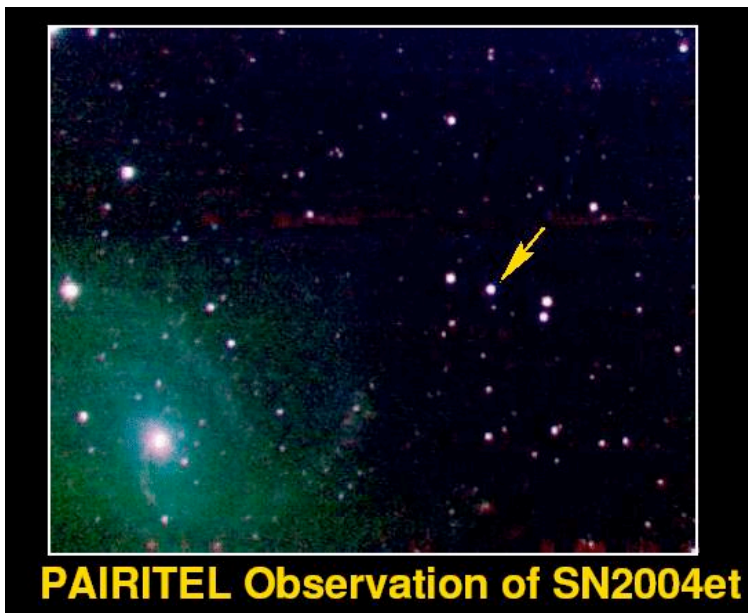
During the coming three years, we should bring the CfA sample to a total of about 200 well-observed SN Ia in the Hubble flow with $cz > 2500$ km/s. This data set on its own will provide an adequate platform for combination with the results from ESSENCE (at $z \sim 0.5$) and PANS (at $z > 1$) so that there is negligible error contributed by the low- z sample for determinations of w at the 10% level. Independent data from other sources will provide external checks that are essential to revealing calibration flaws and other systematic errors.

Testing Systematics: the Abundance Factor “More of the same” will be of decreasing interest by 2008. One of the most interesting systematic effects, which is well established, is that SN Ia in Elliptical galaxies are significantly different from SN Ia in Spirals. Hamuy et al. (1996) and later Riess in his thesis showed that the most luminous SN Ia are found only in spiral galaxies. While the current incarnation of light curve shape methods accounts for this properly, it could be the source of problems in interpreting the high- z sample if it is not understood.



Together with Peter Garnavich and his student Joe Gallagher, we have begun to do this. Using the FAST spectrograph on the 1.5 meter at Mount Hopkins, we have collected integrated spectra of moderately nearby supernova host galaxies by scanning the entrance slit across the target galaxies. So far, 57 galaxies have been observed, and the metallicity-luminosity relation compared with SN Ia models. We plan to measure line indices both for Spirals and for Ellipticals that have been host galaxies for SN Ia we have observed well. We know the luminosities from the light curves and redshifts, we have the supernova spectra to detect more subtle variations, and we will determine the galaxy metal abundances from emission lines for the Spirals and absorption lines for the Ellipticals. This would be the best way to examine the contribution of metallicity to the Hubble Diagram and to mitigate its systematic effect on the cosmological results.

Something New: One of the most interesting developments in the field is the work by the Carnegie group on infrared light curves. They show evidence that the SN Ia luminosity is very nearly constant independent of IR light curve shape, and the corrections for reddening are, of course, quite small (Krisciunas, Phillips & Suntzeff, 2004; Krisciunas et al., 2004). The present database for IR light curves is slender, but we have an excellent opportunity to complement the southern hemisphere work of the Carnegie Supernova Program by extending our own northern program to the IR. Josh Bloom has resuscitated the 2MASS telescope at Mount Hopkins and its JHK detector as the fully robotic observatory PAIRITEL (<http://www.pairitel.org/>).



The advantages of this system for IR photometry of supernovae are obvious: it can make observations every night of all the bright supernovae, leading to a densely sampled, well-calibrated JHK_s lightcurve for about 20 objects per year. There will be no gaps in observations due to instrument changes, because there are no instrument changes. Instead of being restricted to the very short

integration times used in the 2MASS survey, an automated dither allows deep exposures of 20 minutes or more, so that the supernova survey at PAIRITEL can easily monitor objects found at $K \sim 15$. Based on current discovery statistics, we expect 3 or 4 objects to be available on a typical night, so that the supernova program will occupy about 1 hour per night.

This is completely compatible with the primary purpose of PAIRITEL, which is to obtain IR light curves of gamma-ray bursts. Our aim is to obtain 10% photometry over the interval from -15 days before maximum (should we be so lucky) to $+25$ days past the peak, with 3% photometry at the peak. Our northern hemisphere location, where the most effective supernova searches and most of the bright galaxies are located should be an advantage for work on nearby galaxies. The PAIRITEL system is up and running now. The image of SN 2004et in NGC 6946 was obtained in a single 7.8 second exposure.

Toward our DESTINY: In the next three years, our contribution to learning more about dark energy means combining the low-redshift program described here with the $z \sim 0.5$ program of ESSENCE, and the $z > 1$ PANS program being carried out on *HST*. For the longer term, NASA and DOE have agreed to carry through a Joint Dark Energy Mission (JDEM) and they have funded studies to see what that mission might look like. One mission concept is called DESTINY (<http://destiny.asu.edu/>). Unlike the SNAP concept for JDEM, DESTINY proposes to carry out all the observations with IR detectors, rather than build a complex focal plane of both IR detectors and CCDs.

An important question that needs to be answered is whether a program that uses IR detectors alone can really do an adequate job of establishing the Hubble Diagram over a wide range in redshift, say from $z \sim 0.5$ to $z \sim 1.5$. This means learning the limits of IR measurements at the low redshift end, while shifting the emphasis to restframe UBVRI for the higher redshift end of this sample. The way to learn how to do this is to have excellent data at redshift zero to serve as input for simulations. The large CCD sample in UBVRI from our ongoing CfA work and the forthcoming sample in JHK from our PAIRITEL program will provide just what is needed to investigate the best way forward for a space-based JDEM.

How DETF can help: This program and its kin provide the foundation for the empirical evidence for cosmic acceleration, independent measurement of the Hubble constant, and cosmic age, to say nothing of understanding the properties of thermonuclear supernovae. The work at high redshift is technically demanding and has produced spectacular results, but there is still significant work to be done at zero redshift that will squeeze out the last bit of statistical error, leaving only the more thorny systematic problems. Better understanding of the causes of variation among SN Ia will help with those problems, too. Explicit recognition of this by the DETF will help the agencies place their resources where they have the best effect. The program described here costs only about \$250 000 per year because the telescope operation is part of the CfA. It is a bargain!

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